National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Magnetic Shield Design Modeling and Validation on SWOT Spacecraft Applied to Mars Flux Pinning Orbiting Sample Design

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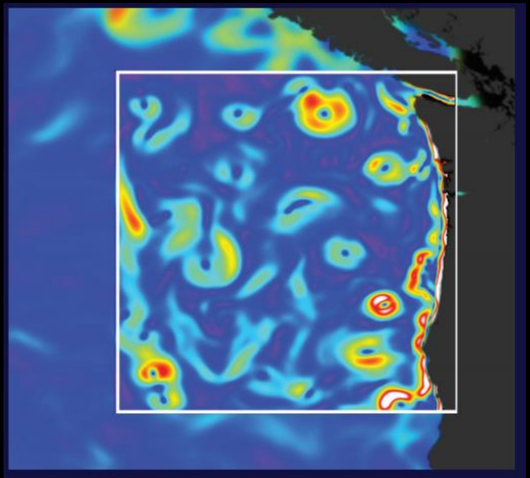
Overview

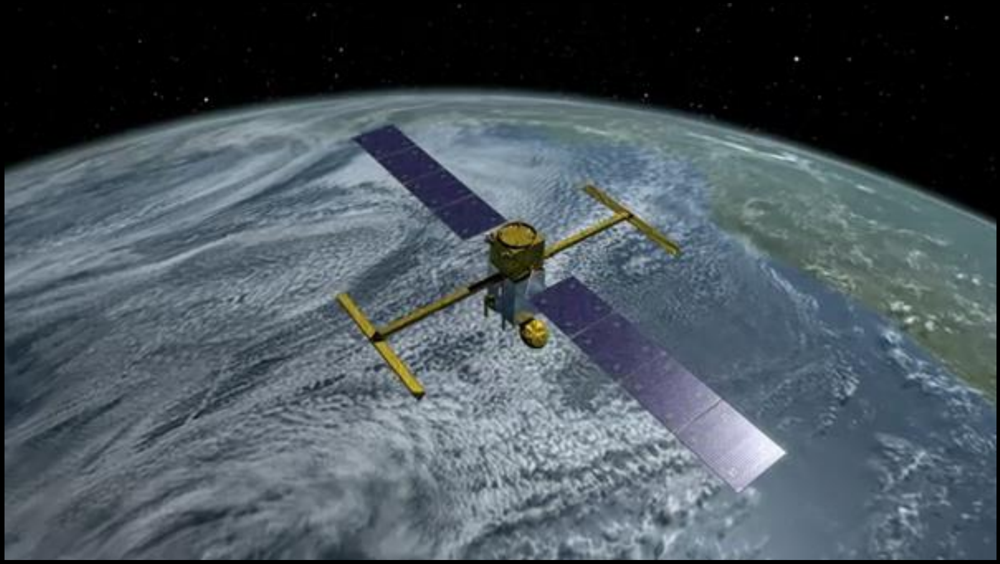
- SWOT mission driving concerns
- Modeling methodology and FEM considerations
- Correlation to measurement
- Modeling methodology applied to potential Orbiting Sample for Mars Sample Return mission concepts
- Baseline and shield selection
- Mass optimization efforts
- Conclusion

SWOT Mission

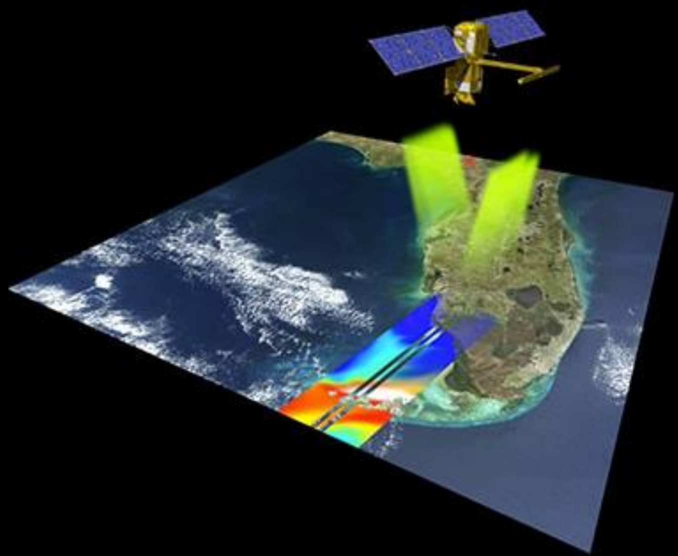
- NASA/CNES/CSA joint mission to survey surface water height with unprecedented accuracy (0.8 cm) and spatial resolution (4 km^2)
- Proposed 2020 launch
- TOPEX/Poseidon and JASON missions collected invaluable data on ocean heights, but have insufficient resolution for:
  - Coasts/rivers/lakes
  - Small scale ocean kinetics
- KaRIn instrument provides this capability



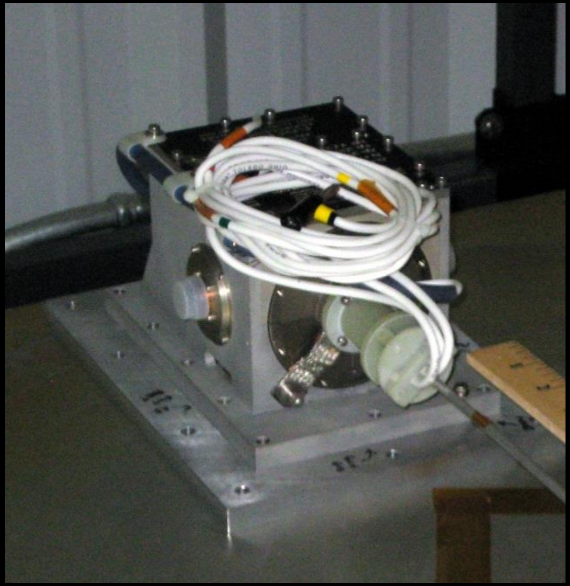
Simulated SWOT data off the coast of Oregon, USA.
Image; C. Ubelman, J. Howard, NASA



KaRIn Instrument and EIKs



Source: http://swot.jpl.nasa.gov/gallery/multimedia/index.cfm?FuseAction=ShowMultimediaGallery&mmID=14



- **Ka**-band **R**adar **In**terferometer
- RF power generated by an Extended Interaction Klystron (EIK)
- EIKs contributed by CSA/CPI
- EIK uses electron beam focused by large permanent magnet
- 63 A-m^2 dipole moment
  - 1 T (10000 gauss) measured at surface of magnet
- Redundant: a second EIK is a “cold” backup

Magnetic Cleanliness Mitigation

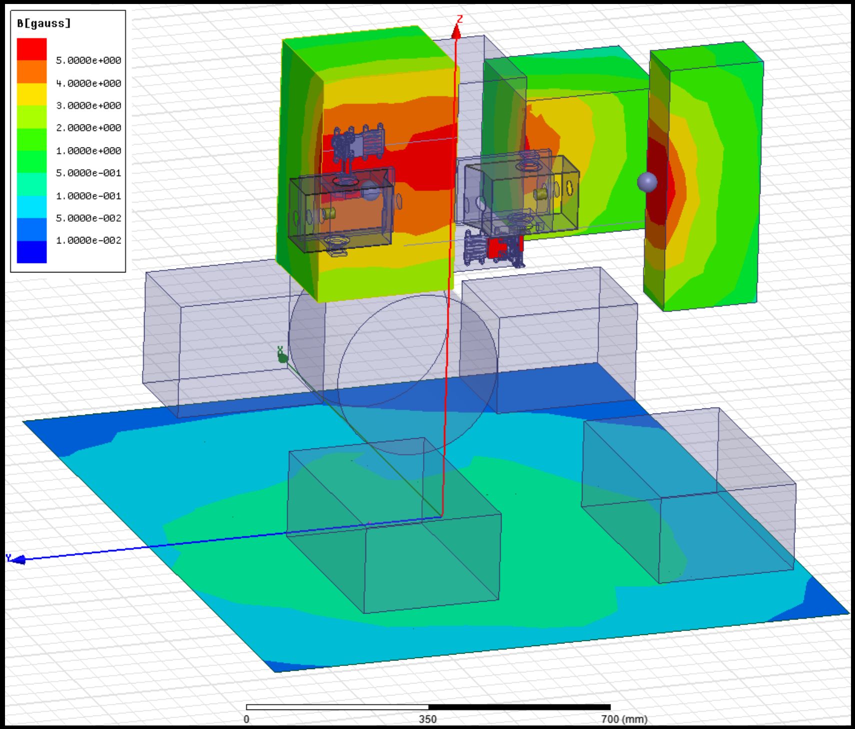
- Magnetic cleanliness programs generally involve the following, most of which add mass and volume
  - Minimizing use of magnetic materials
    - Strong magnetic field strengths can be essential to function
  - Distance
    - Limited by required spacecraft geometries
  - Compensation/cancellation
    - Self-compensation (especially with redundant systems) doesn't add mass, but may be insufficient
    - Additional compensation magnets can be added if small area needs minimization
  - Shielding
    - Adds mass but can be very effective

SWOT magnetic cleanliness concerns

- Sensitive magnetic devices on SWOT
  - RF: ferrites, circulators, isolators
  - Attitude control system: magnetometers, gyroscopes
- Previous evaluations that EIKs should be oriented with dipole moments in opposition (self compensation)
- Exceptionally large field levels would still be present within the spacecraft
- Proposed shield parameters:
  - Thickness: 0.5 mm, 1.5 mm
  - Material: mu-metal, steel

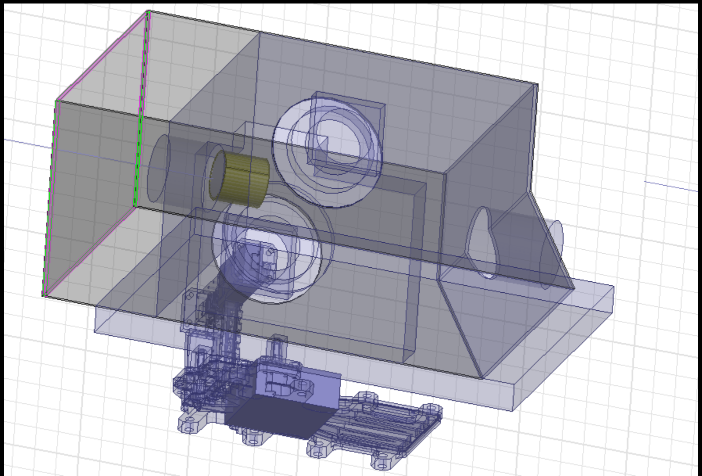
Red → > 5 gauss
Blue → < 0.01 gauss

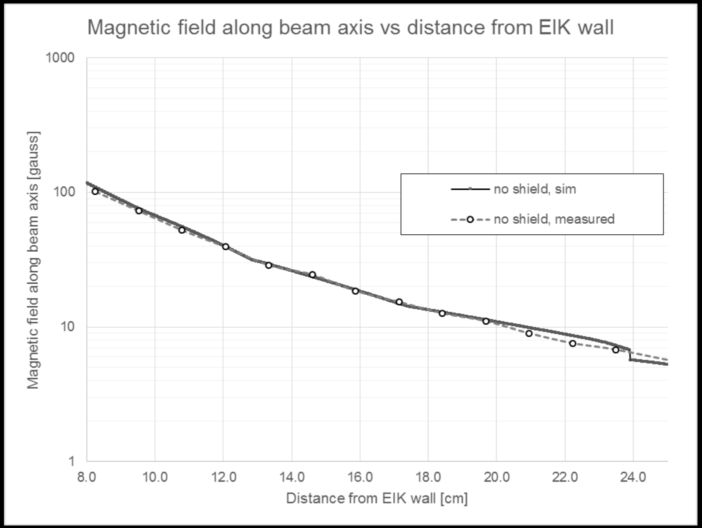
Worst case DC magnetic field at sensitive victim locations [gauss]	
Subsystem	**No shield**
Location A	0.22
Location B	6.3
Location C	9.0
Location D	22.5



SWOT EIK Modeling Methodology

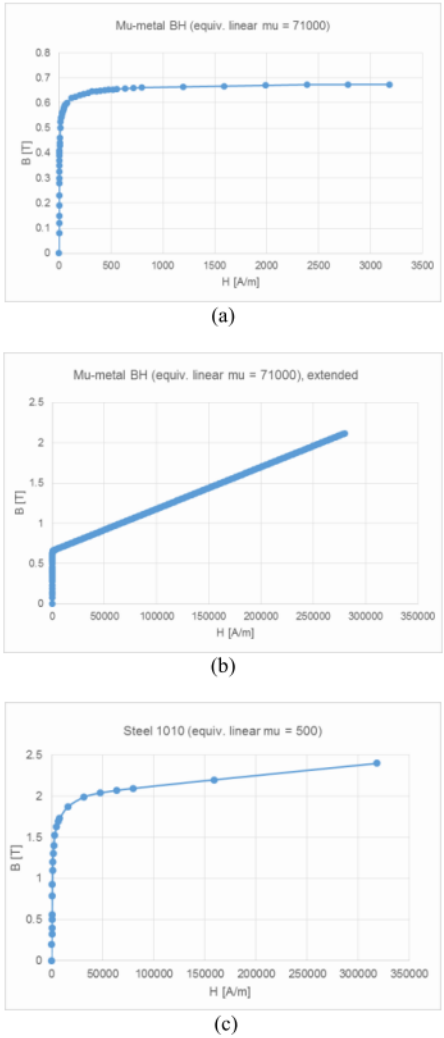
- 3D Magnetic FEM Solver
- Magnetic source: coil of wire
  - Coil chosen vs. permanent magnet models as it allows for straightforward calibration of magnetic source to measurement
  - 22 mm dia x 20 mm wire coil
- Excitation current determined by measurement correlation to Engineering Model EIK





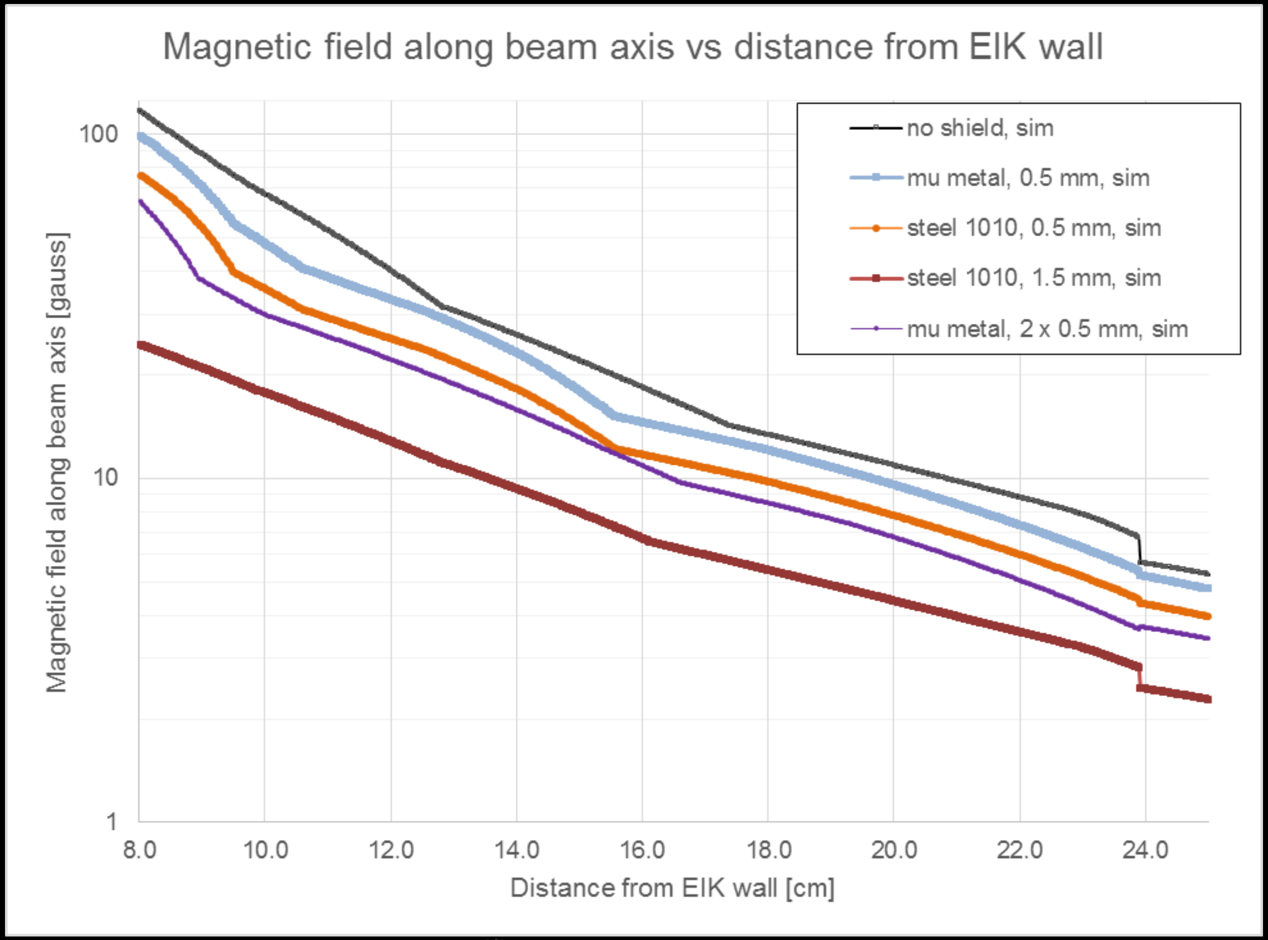
Model Configuration

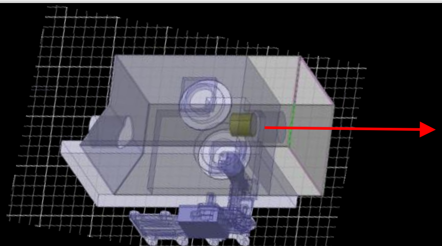
- Inaccuracies in nonlinear parameter extraction at high field levels needed to be addressed
  - B-H curves extended
  - Nonlinear residual reduced significantly: 1e-3 to 1e-7



B-H curves for shield materials: (a) mu-metal, (b) mu-metal extended to H = 2.8 x 10^5 A/m. (c) cold rolled steel 1010

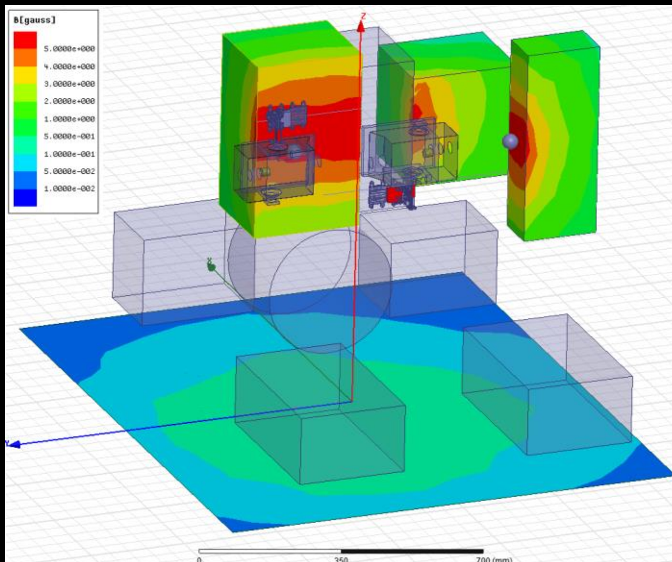
Shield modeling results



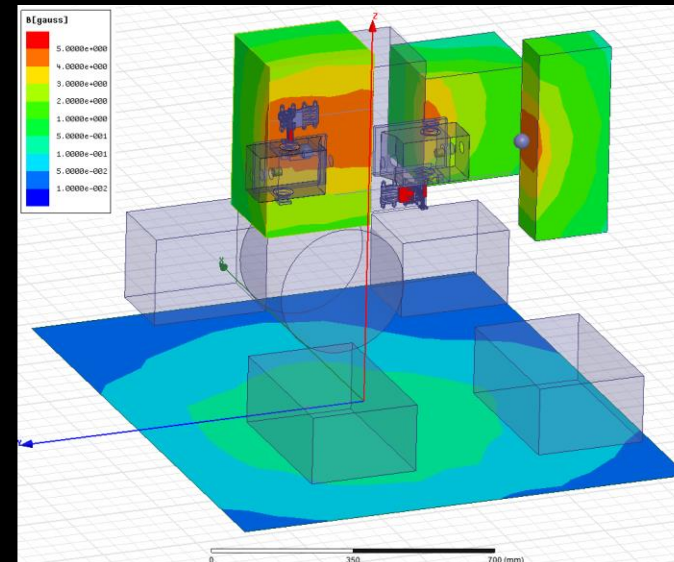


Spacecraft model with shields

Mu metal, 0.5 mm (20 mil)



Steel 1010, 0.5 mm (20 mil)

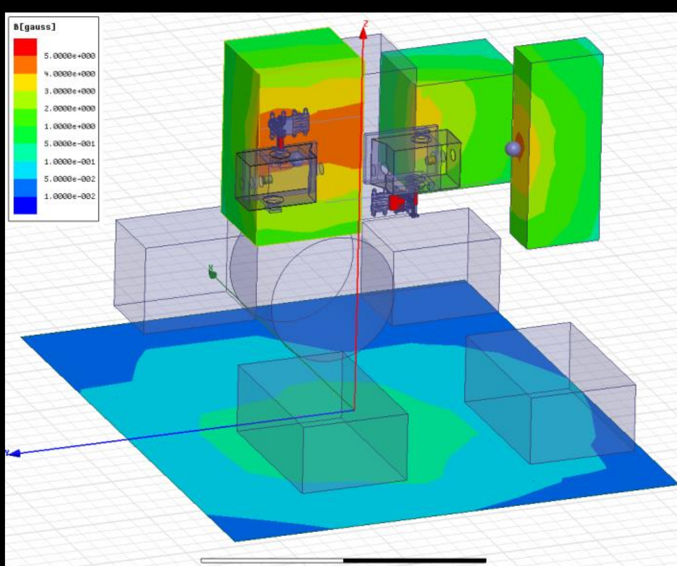


Worst case DC magnetic field [gauss]		
Subsystem	mu metal	steel
Location A	0.17	0.17
Location B	6.7	5.8
Location C	8.3	6.7
Location D	21.0	17.7

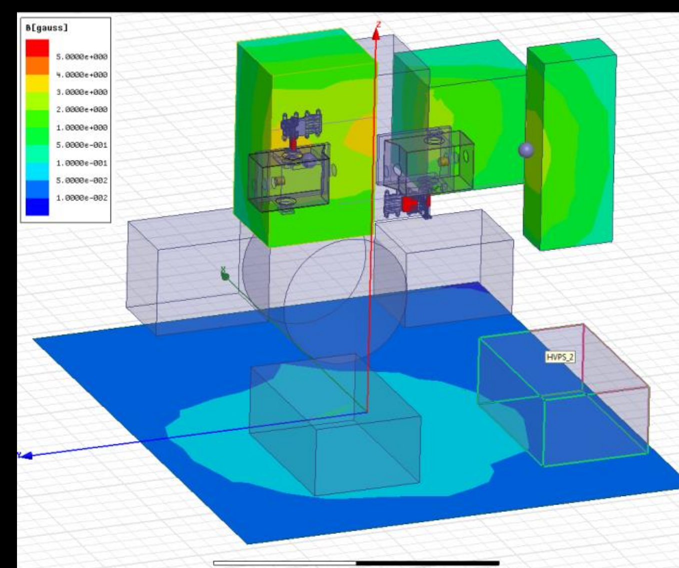
Red → > 5 gauss

Blue → < 0.01 gauss

Mu metal, 2 x 0.5 mm (2 x 20 mil)



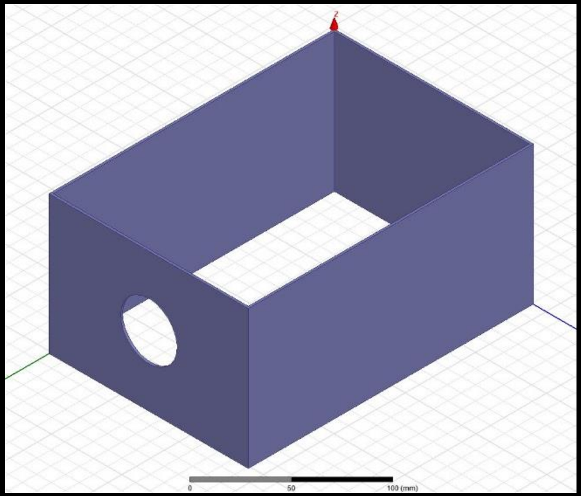
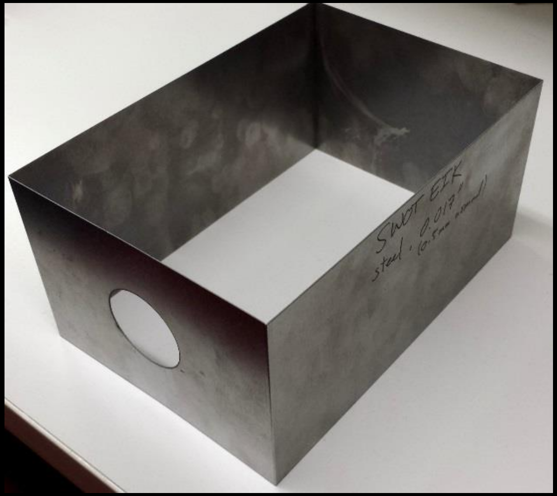
Steel 1010, 1.5 mm (60 mil)



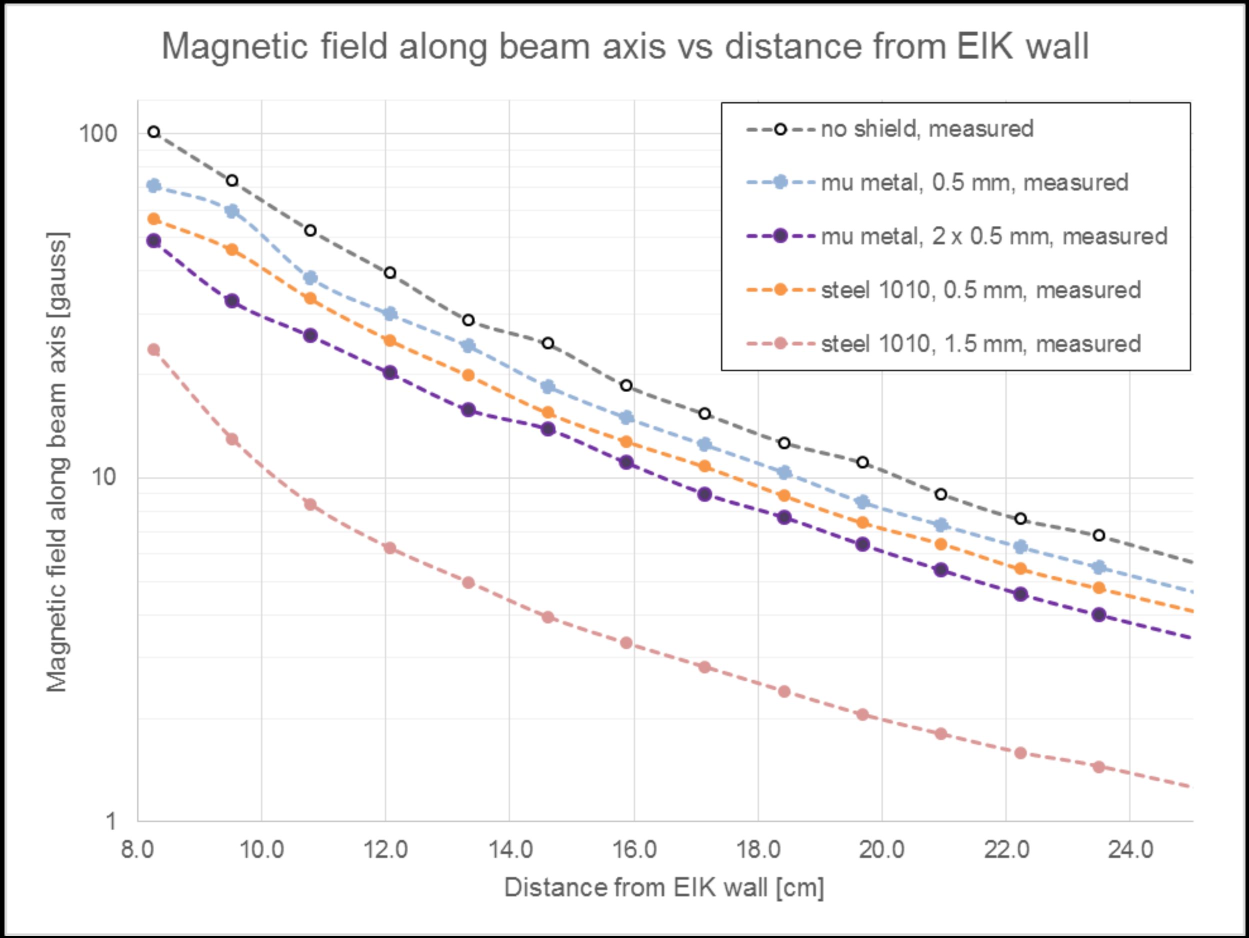
Worst case DC magnetic field [gauss]		
Subsystem	mu metal	Steel
Location A	0.16	0.10
Location B	5.4	3.6
Location C	5.6	3.5
Location D	16.6	9.8

Shields built

- Mu-metal 0.63 mm (25 mil), also 2 x 0.63
- Cold rolled steel 1010, 0.43 mm (17 mil)
- Cold rolled steel 1010, 1.5 mm (60 mil)

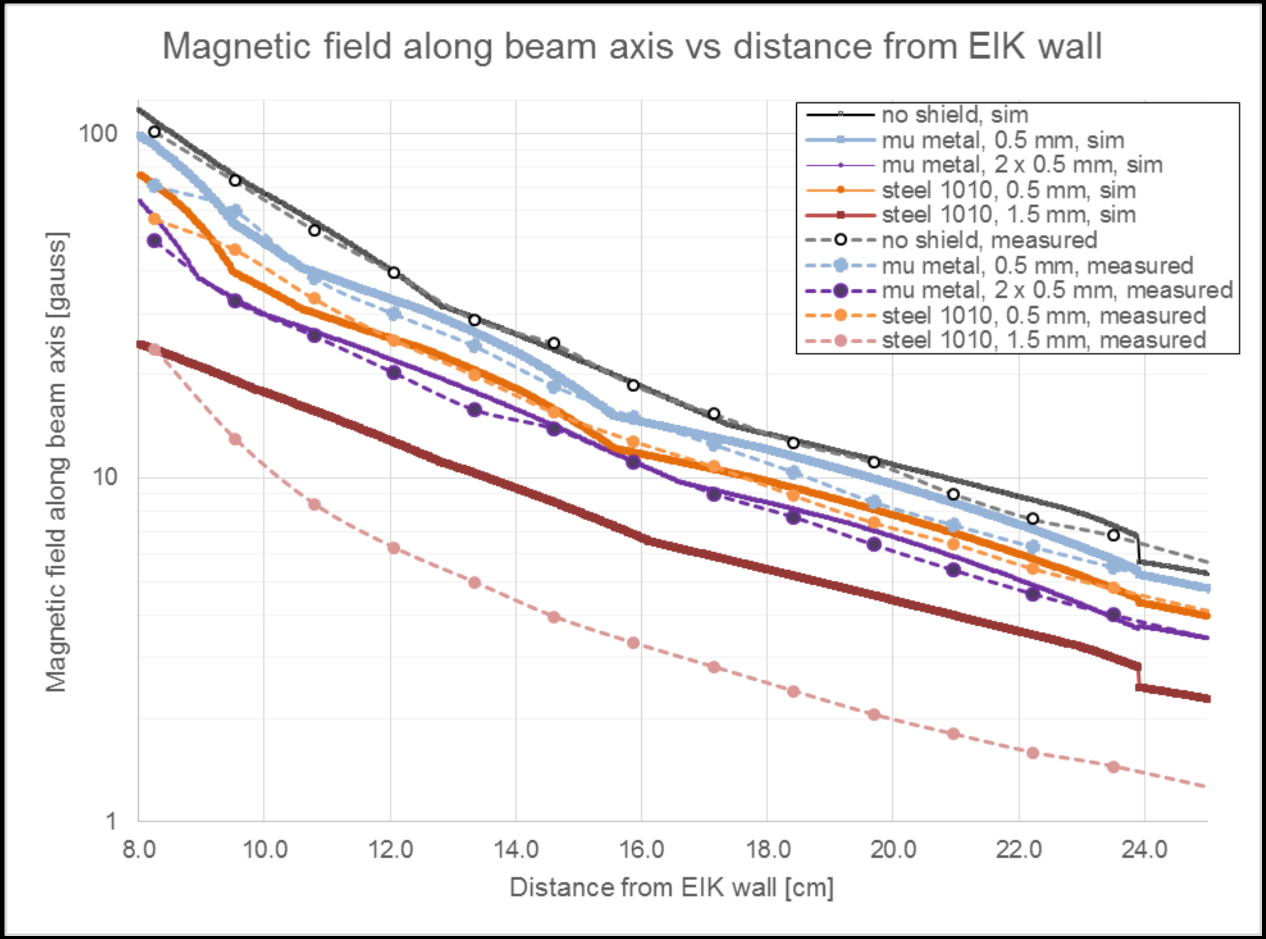




Measured values

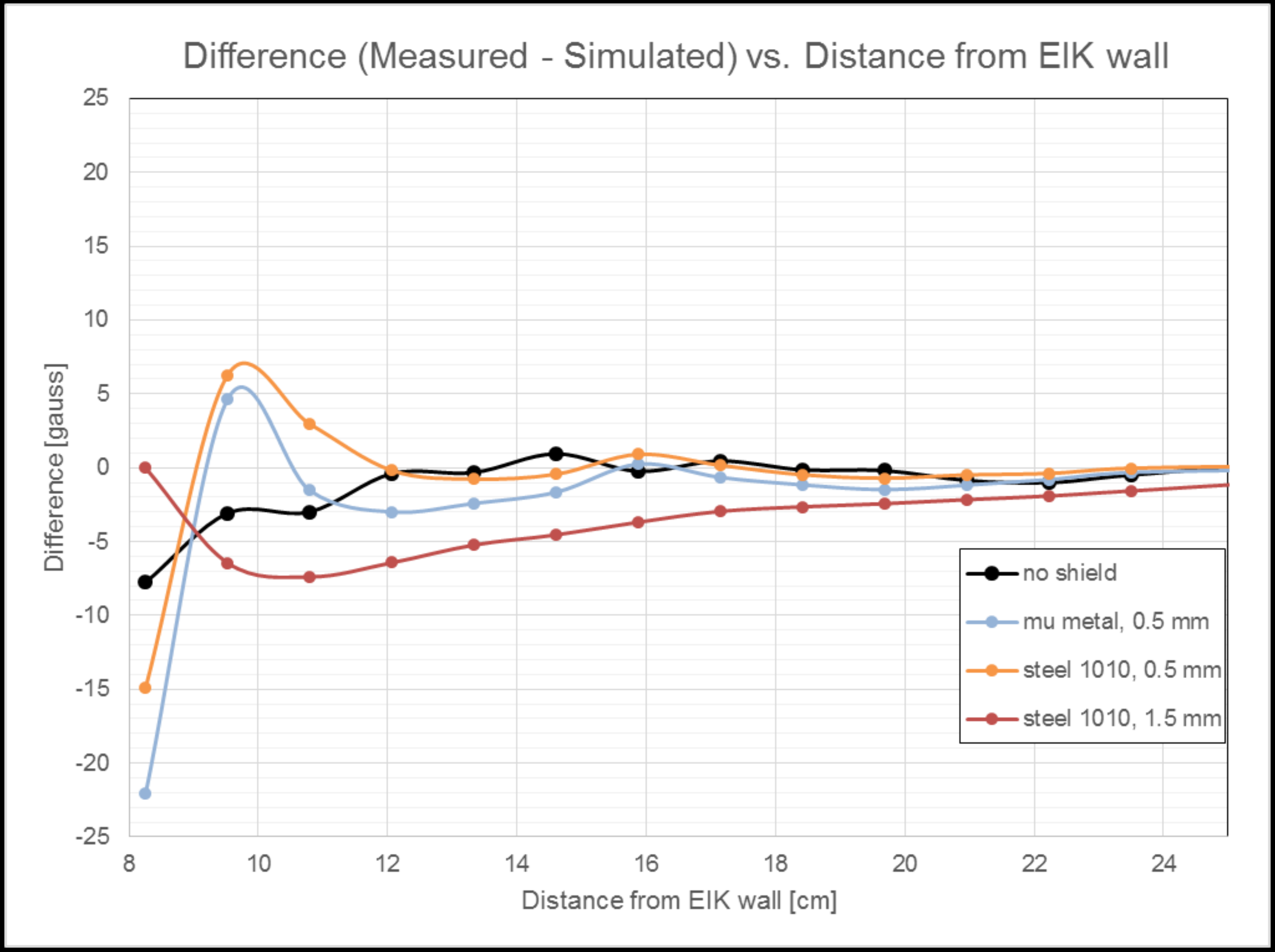


Measured with calibrated gaussmeter and single-axis probe

Model vs. measurement

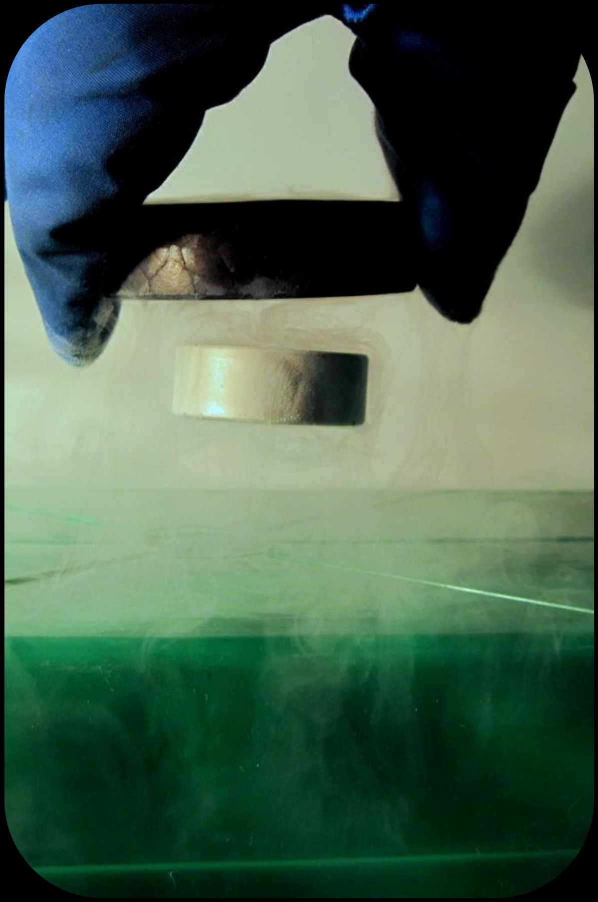


Model vs. measurement: difference



Flux Pinning Interface for Orbiting Sample

- Magnetic modeling techniques developed for SWOT were directly applied to options for a Mars Sample Return (MSR) mission concept
- A surface mission like Mars 2020 is expected to collect core samples
- A potential future Mars Sample Return (MSR) mission would:
  - Place sample tubes into a ball (“OS”)
  - Put ball into orbit
  - **Capture ball**
  - **Clean without touching**
  - Launch to earth
- Flux-pinning uses superconductors and magnets to provide stable control interface without touching contaminated sample ball
- See next slides courtesy of Co-PI Laura Jones-Wilson



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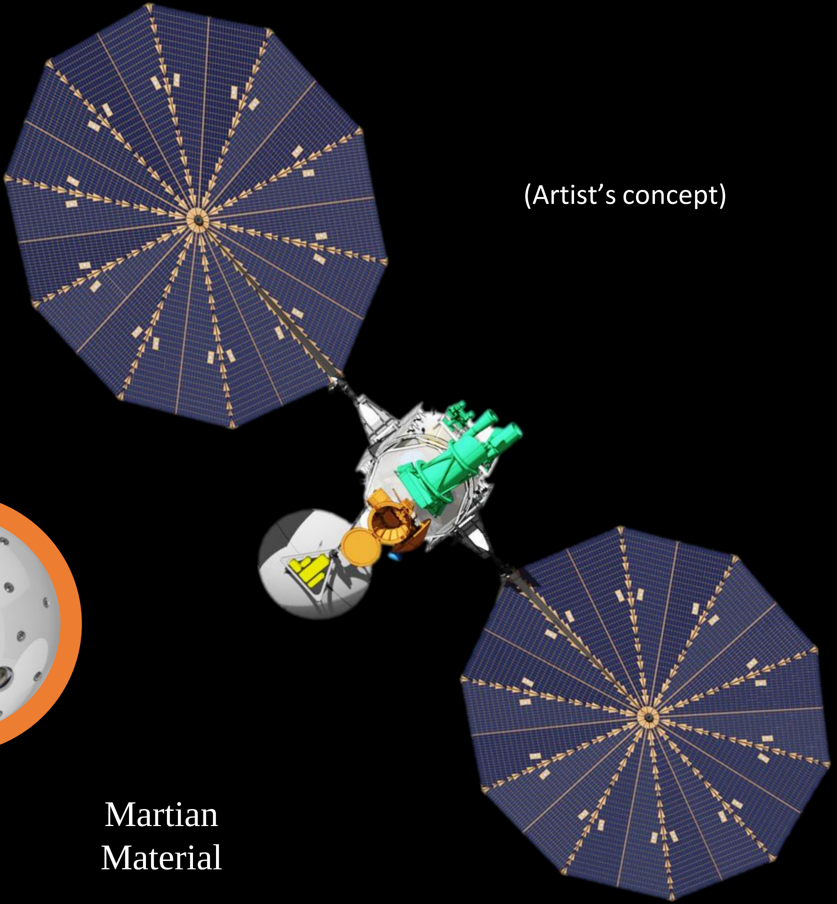
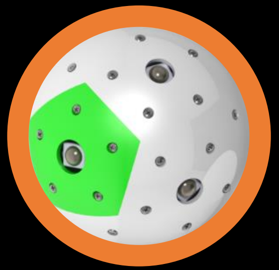
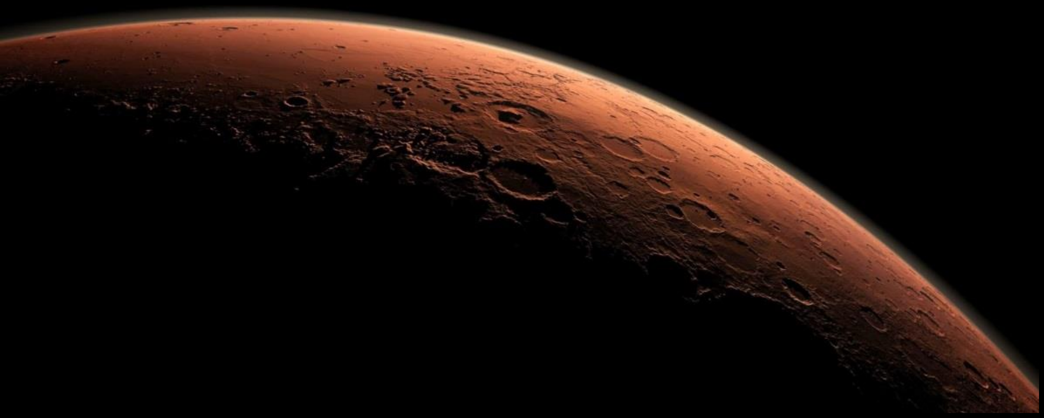


(Artist's concept)

Mars Sample Return (MSR)



Martian
Material



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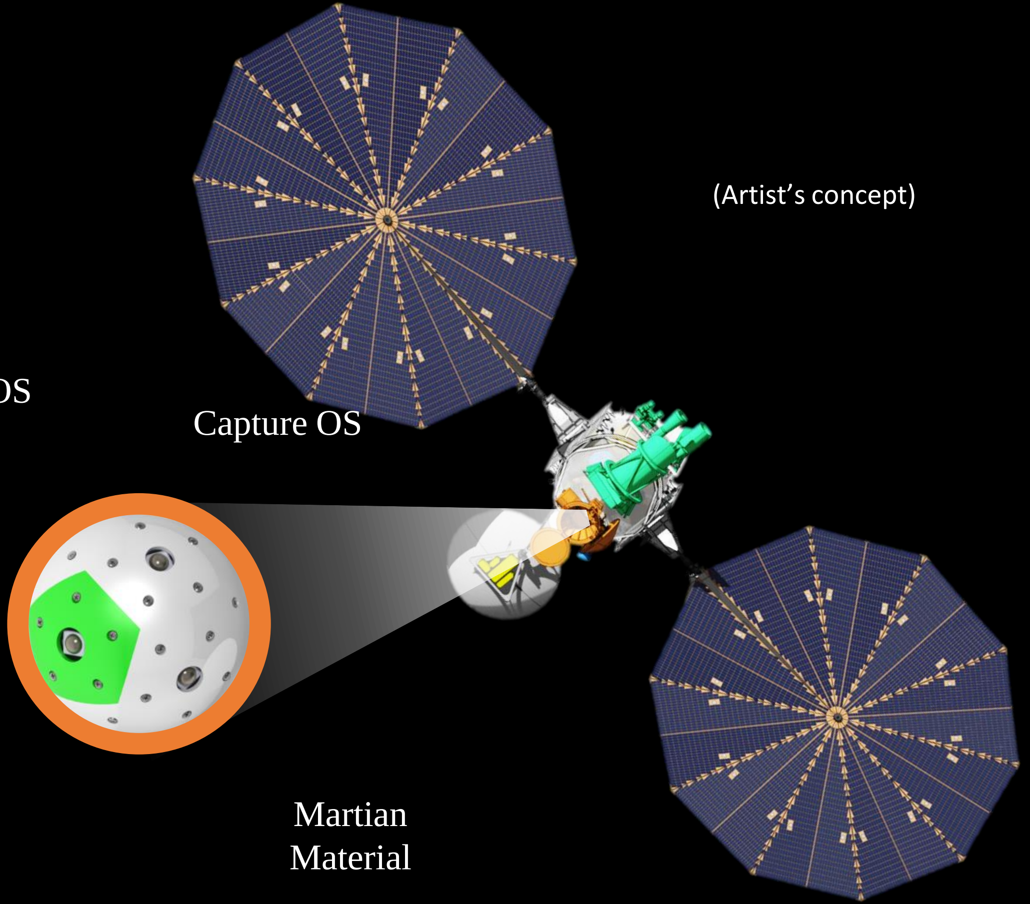
Stabilize OS



(Artist's concept)

A. Capture
(attractive forces bringing in OS with set of initial conditions)

B. Proximity operations
(stabilizing the OS from its initial conditions, manipulating SRO to be in control of OS dynamics)

C. Cleaning operations
(actively manipulating the OS to present different faces to the cleaning mechanism, maintaining control in the presence of cleaning forces/torques)

D. Docking
(bringing the separation distance of the OS-SRO to zero to bring the system into the next phase of the processing)

E. Tolerating off-nominal mission scenarios
(impact of OS with SRO, rapidly spinning OS, missing magnets, etc.)

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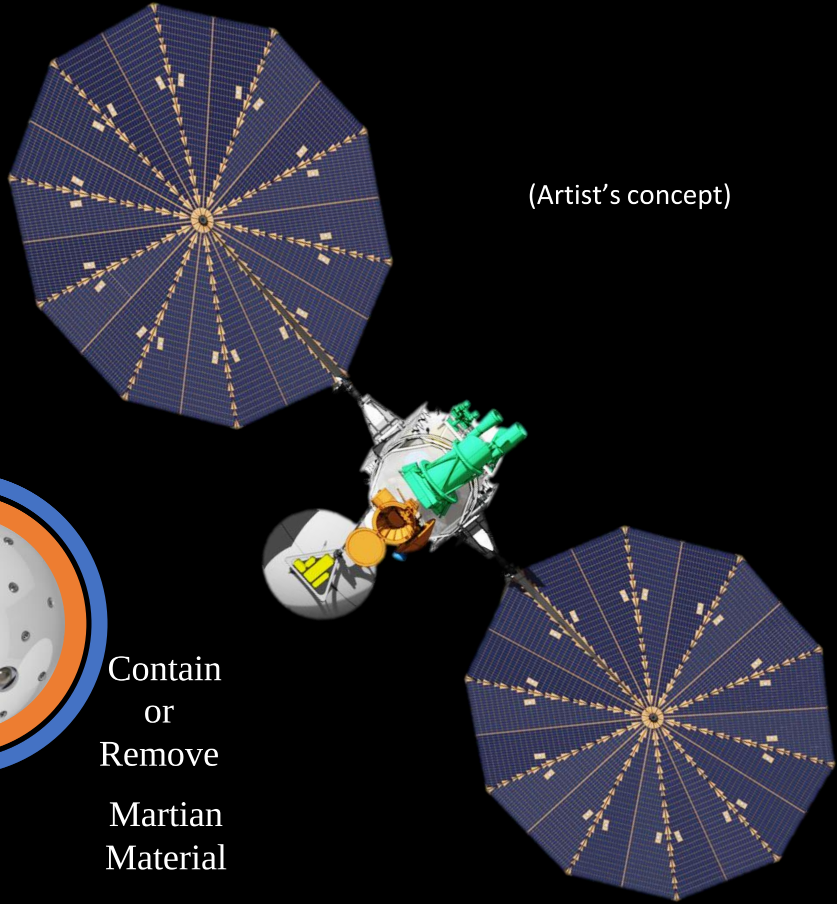

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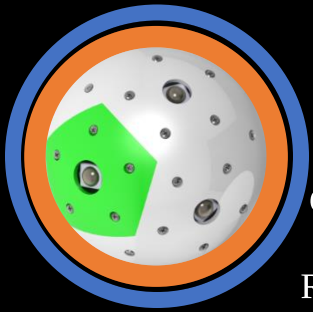

Contain
or
Remove

Martian
Material

Breaking the Chain

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(attractive forces bringing in OS with set of initial conditions)

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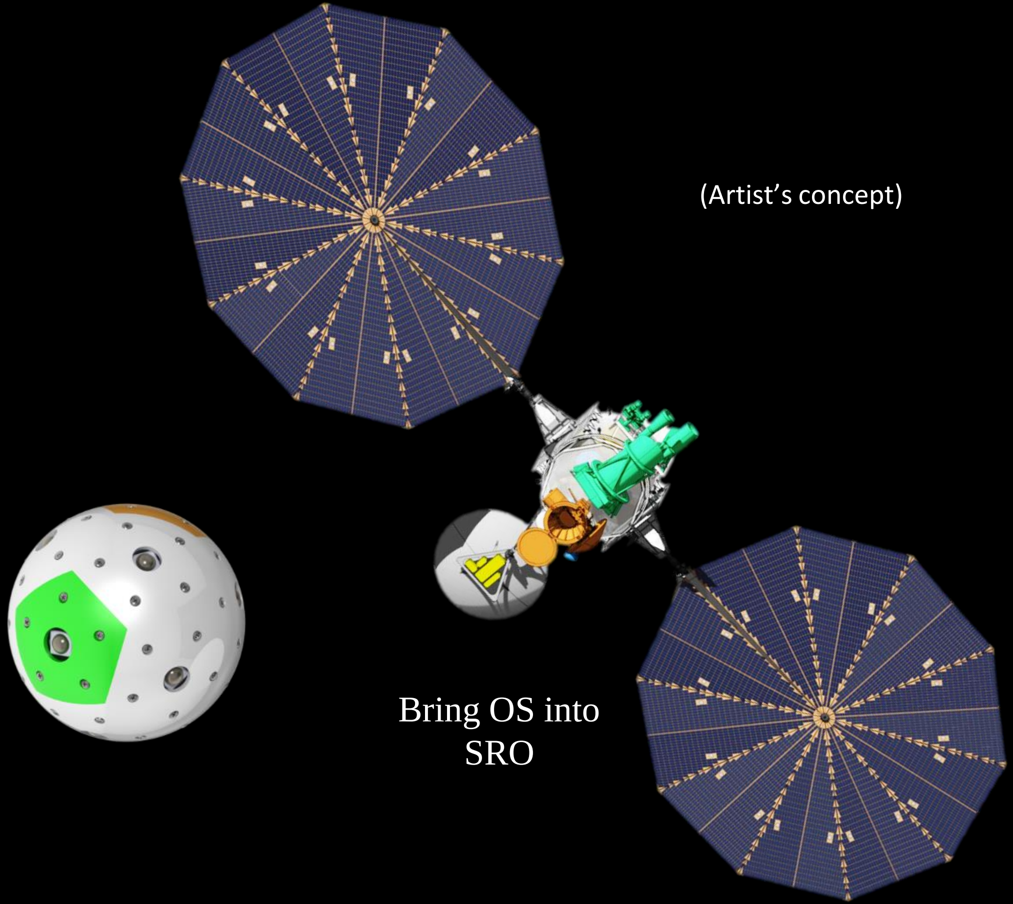
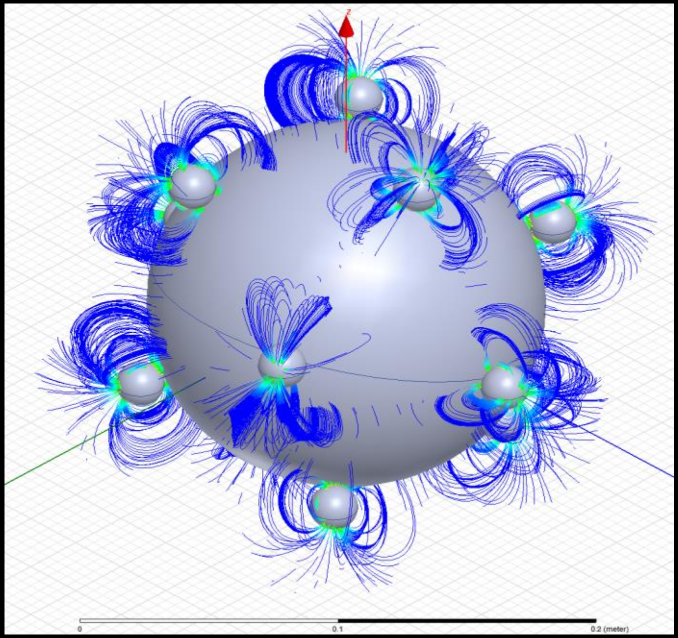


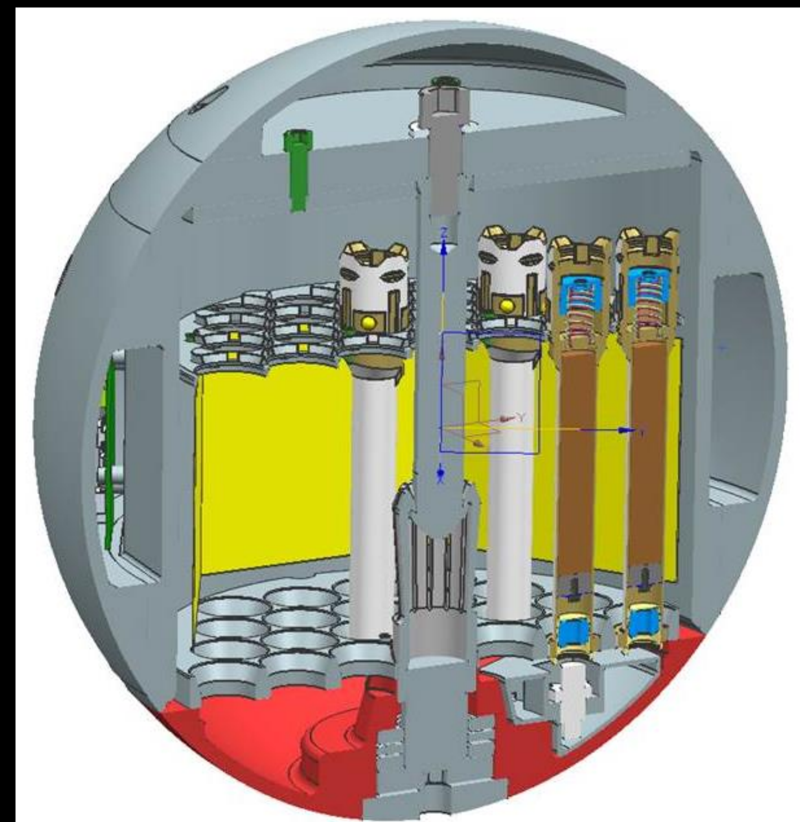
FPOS Magnetics Challenge

- Core samples should preserve critical magnetic information about Martian geology
- Fields >0.5 mT (5 gauss) may permanently erase this data
- Sample ball has very strong magnets: almost 1 T, 2000x above limit!
- **Is it feasible to use magnets given the necessary added mass for mitigation?**
    - Mass target: 2 kg. To start...
    - Also need to consider exposure throughout process
    - If not, FPOS could be eliminated as an OS option

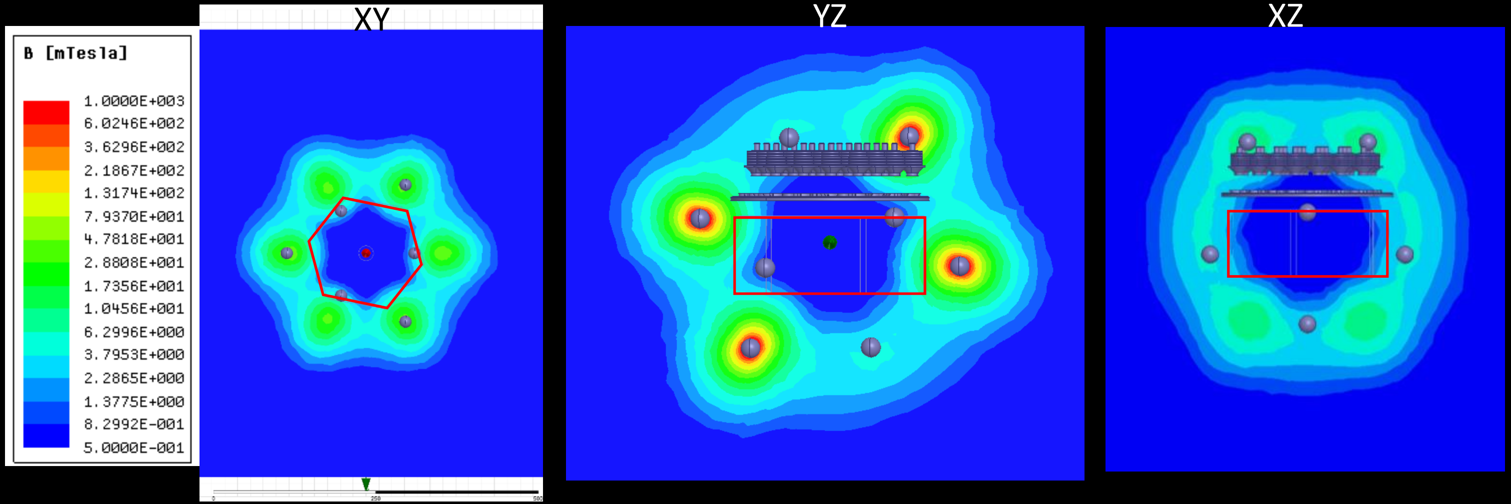


Preliminary prototype Orbiting Sample (OS) and keep-out zone (KOZ)

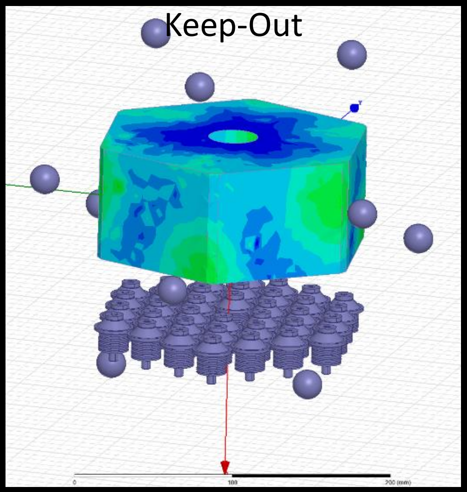
- 12 magnets on surface in dodecahedron (not shown here)
- Yellow portion is the exterior of the magnetic "keep-out zone" surrounding the samples
- Samples are loaded into a canister, which are then loaded into OS

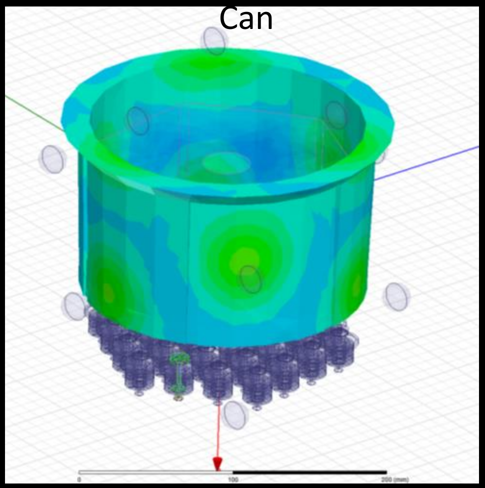


Baseline



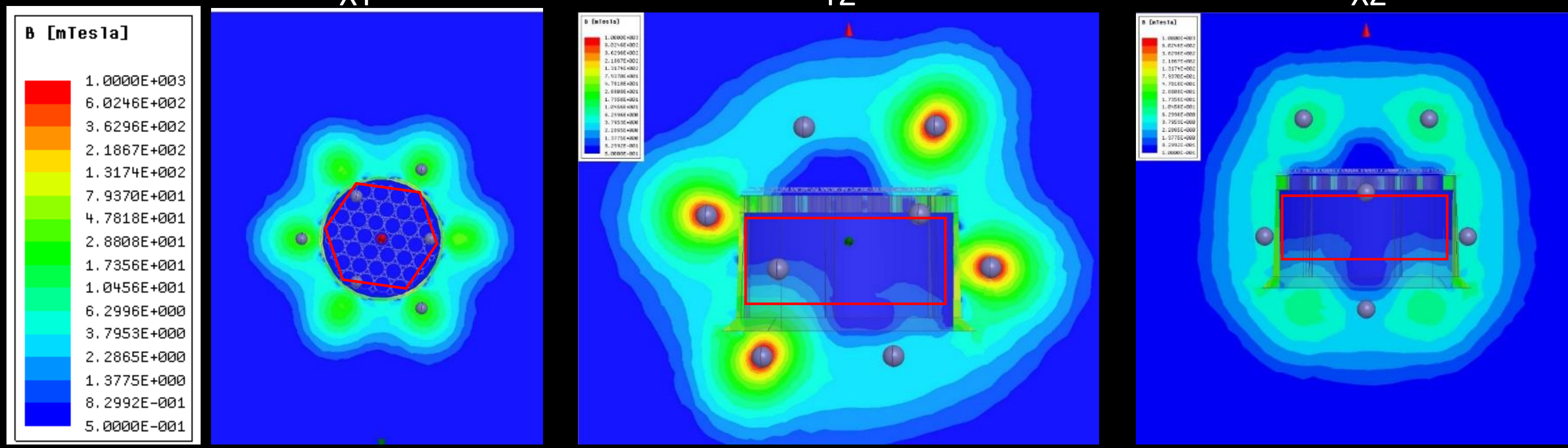
Blue = meet req





Steel 1010 shield on inner can

XY YZ XZ



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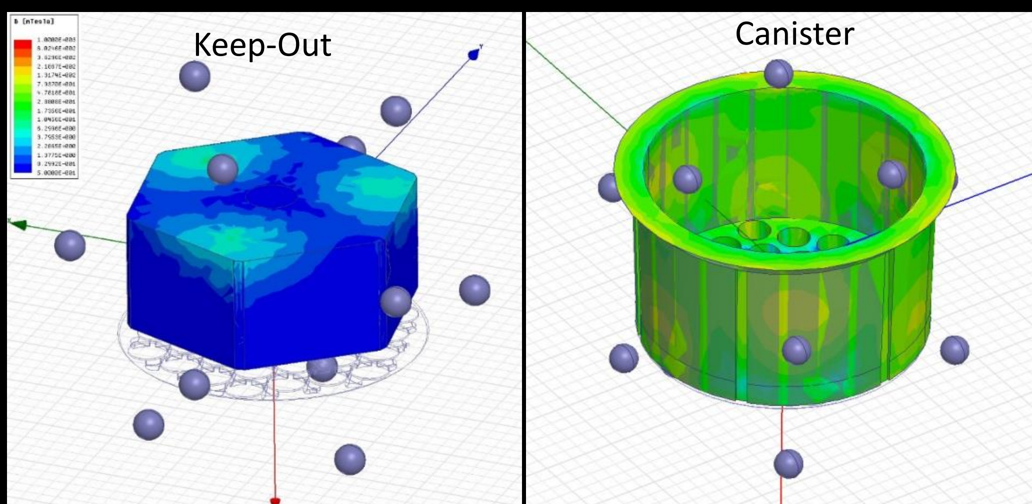
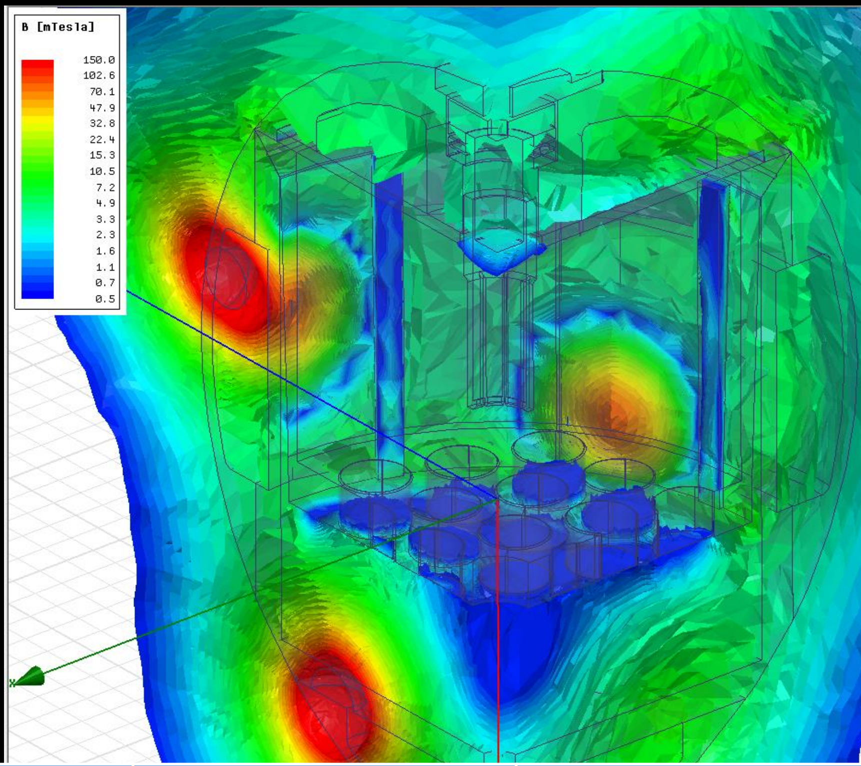
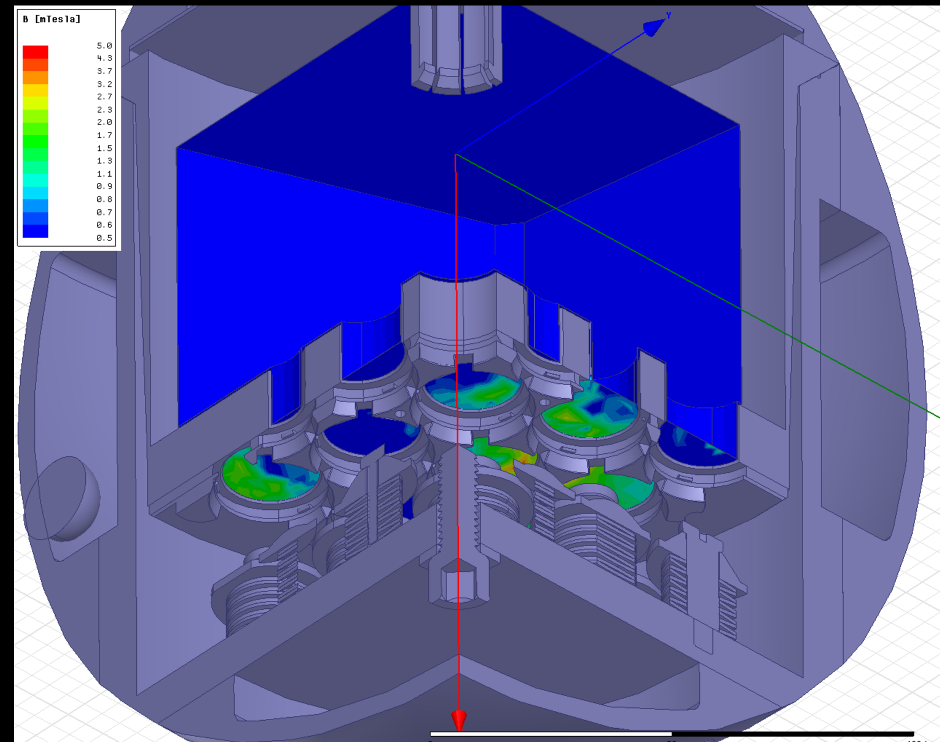


Mass implications of basic steel shield



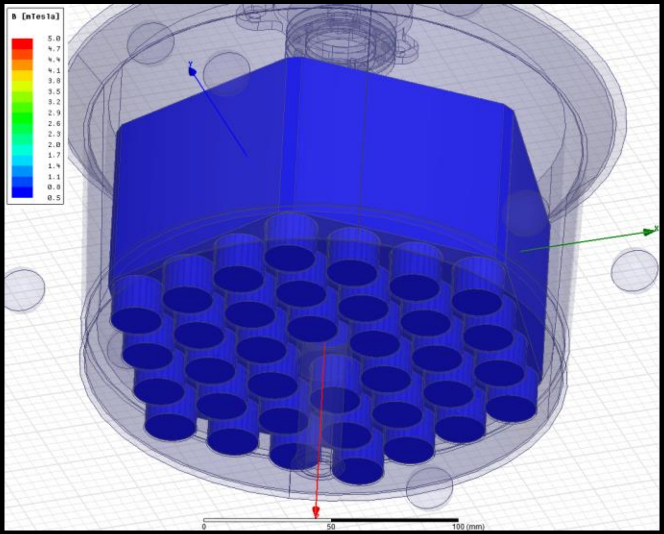
Attempt #	Shield Thickness		Added Mass [kg]
	Lid	Can	
1	4mm	~4-8mm	**5.67 (margin available)**

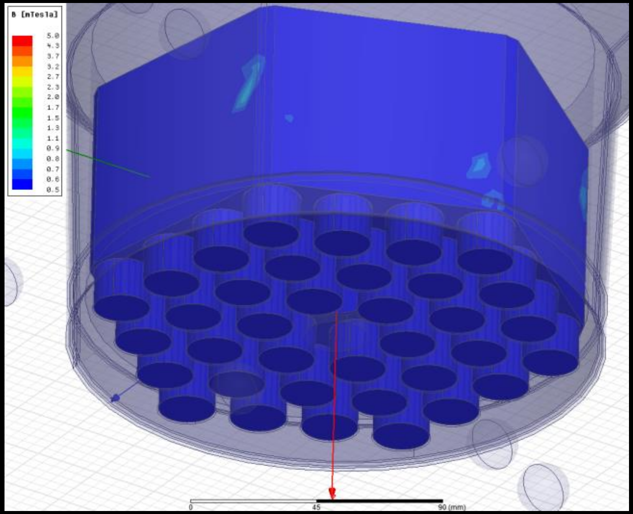


Attempt #	Shield Thickness		Added Mass [kg]
	Lid	Can	
3	1 mm	~1-5 mm	**3.72 (margin available)**

Mass optimization to meet 2 kg target

- Need to use dedicated structures to optimize mass
- 2 kg single shield (1.7 mm thick)
    - Still met requirements
    - Can we push it further?

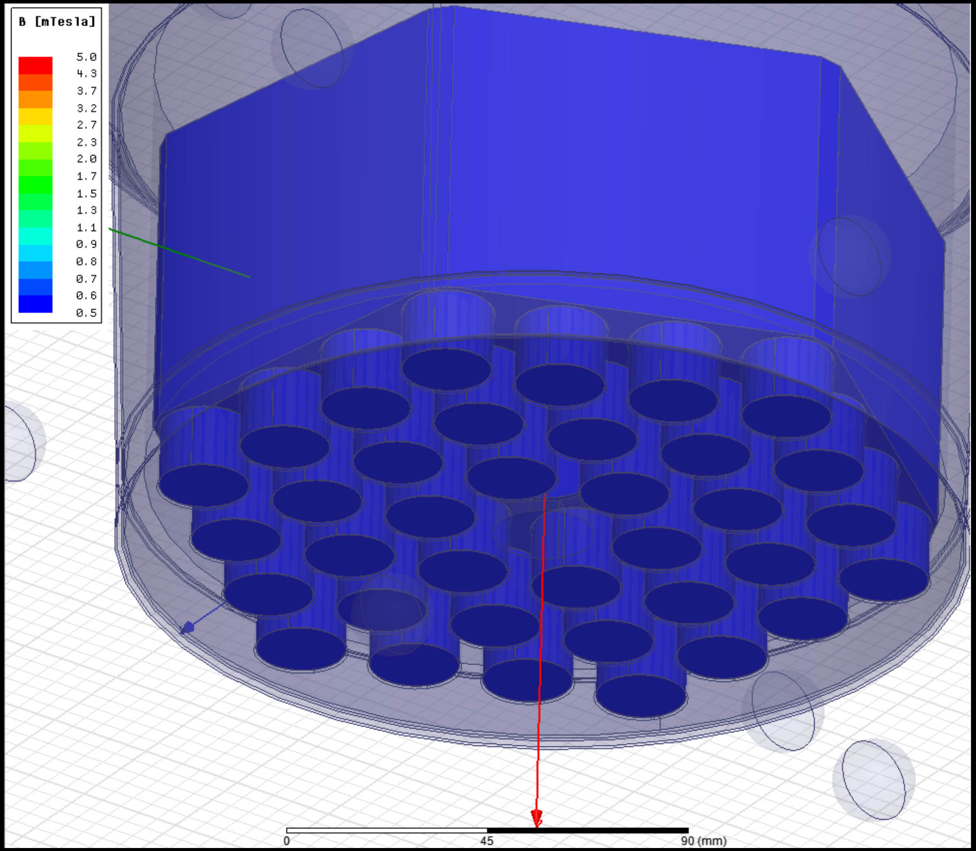




- 1 kg single shield (0.86 mm thick)
    - Slight exceedances.
    - 1 kg may be possible…

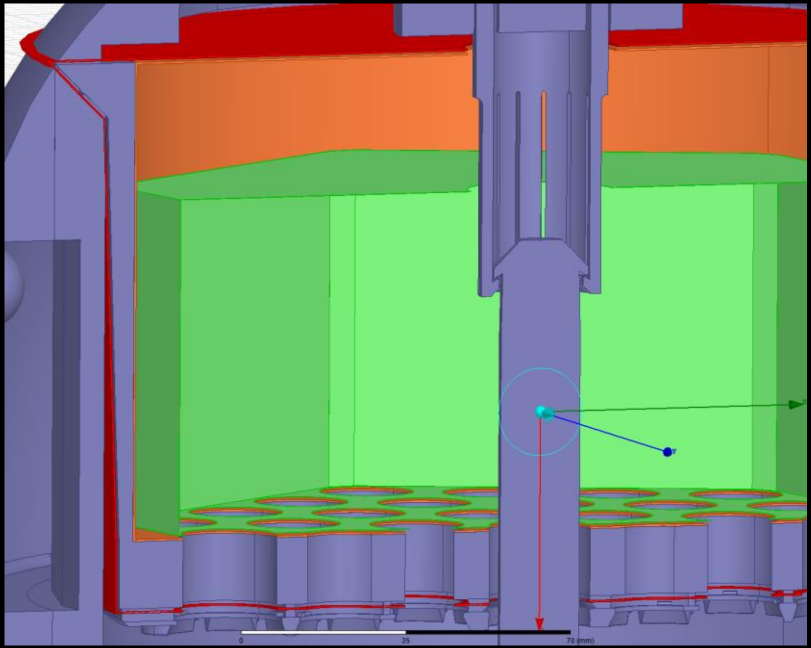
Mass optimization to meet 1 kg target: double shield

- 1 kg double shield meets requirements
- Project requested further mass reduction, targeted 0.5 kg added mass

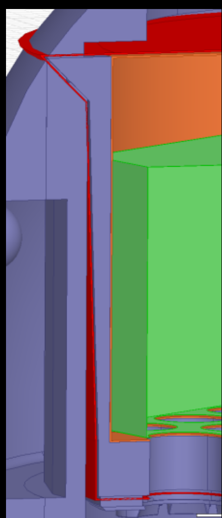


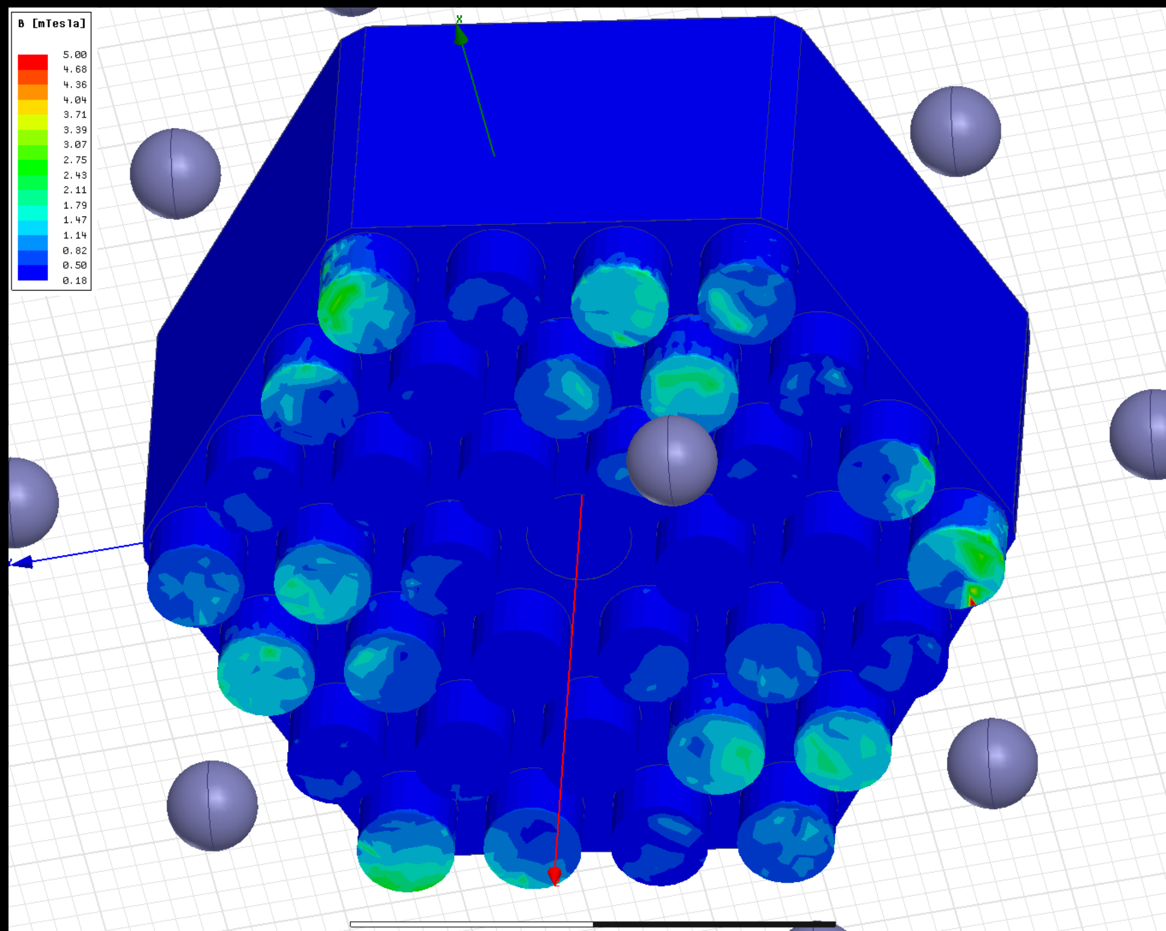
Further mass optimization

- 0.775 kg total “steel plated can”
  - 0.43 mm thick
  - Potentially-displaced mass of structural aluminum: 0.268 kg
  - **Net added mass: 0.507 kg**



Double shield, 0.775 kg total (0.43 mm thick ea.)





Conclusion

- FEM modeling techniques can be an invaluable tool in guiding magnetic cleanliness design trades and requirements
- Modeling saturation effects in high field environments requires careful consideration